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Magnetic Tunnel Junctions and Spin Torque Nano-Oscillators in RF Applications

Report to Professor Mircea Stan by
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ABSTRACT

This document seeks to document our exploration into the possibility of utilizing magnetic tunnel junctions (MTJs) and spin torque nano-oscillators (STNOs) in RF applications, such as compact on-chip tunable microwave signal sources and tunable RF filters. The final report will explain MTJs and STNOs, describe the proposed applications, and present relevant simulation results obtained from the STNO model developed by Mehdi Kabir and Mircea Stan at the University of Virginia.

1. INTRODUCTION

The magnetic tunnel junction (MTJ) is a spintronic device that consists of two ferromagnetic metal layers separated by a thin insulating layer. One of the metal layers has a fixed magnetization, and is called the pinned layer. The other metal layer has a variable magnetization, and is called the free layer. The magnetization of the free layer can be changed by applying some critical current to the MTJ. The insulating layer is made very thin so that electrons can tunnel between the metal layers. The tunneling current is dependent on the relative orientations of the metal layers. If the magnetizations are oriented in the same direction (parallel), the tunneling magnetoresistance (TMR) will be less than if they are orientated in different directions (antiparallel). This property of MTJs means they can be used as a memory element, similar to a floating gate transistor. MTJ based spin-transfer torque RAM (STT-RAM) is considered to be a strong potential candidate for universal memory [1].

MTJs also have another interesting property: if a DC current is applied to an MTJ that is less than the critical current required to flip the free layer magnetization, but enough to cause procession, stable microwave oscillations will be produced. MTJs that take advantage of this effect are called spin torque nano-oscillators (STNOs). STNOs can be used in many exciting on-chip mixed-signal and RF applications. These applications include compact and high-q microwave signal sources, RF filters, phase-locked loops, and phased arrays. All of the above STNO applications also have the added benefit of having easily tunable operating frequencies.

An important thing to note about MTJs and STNOs is that they can be readily integrated into the backend of a regular CMOS process [2]. There is no need for new and complex fabrication methods or facilities. The rest of the paper is organized as followed. Section 2 describes the many potential applications of MTJs and STNOs. Section 3 describes the experimental methods we used to investigate STNO-based RF filters. Section 4 contains our results and simulations, and we conclude in section 5.

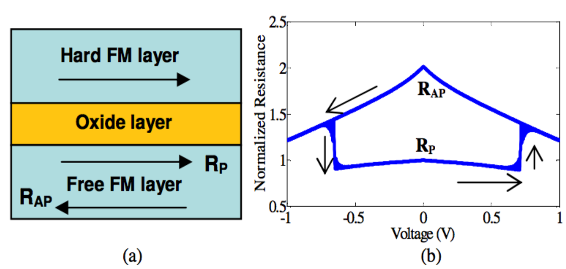

Figure 1 a) The basic MTJ device and b) the normalized resistance VS voltage for parallel and antiparallel states. Obtained from [1]

2. APPLICATIONS

2.1 STT-RAM

Currently, memory requirements are fulfilled by a range of different technologies: SRAM, DRAM, Flash, etc. Each technology has it's own benefits and tradeoffs. There is an ongoing search for a universal memory that has all of the ideal properties of a memory: high performance, high density, high endurance, low power, and non-volatility. MTJ based STT-RAM is considered to be one of the strongest candidates for universal memory. In STT-RAM, data is stored in relative the magnetization of the metal layers. If they are parallel it can be considered a "0," and if they are antiparallel it can be considered a "1."

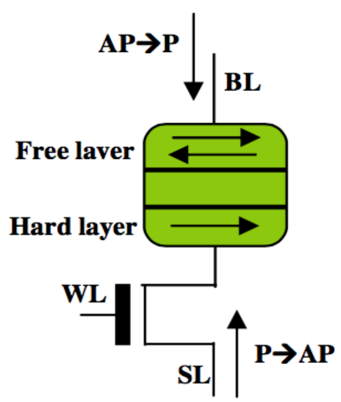

Figure 2: A basic STT-RAM bitcell. Obtained from [1].

2.2 Hybrid CMOS-MTJ Circuits

MTJs can be combined with traditional CMOS technologies to create hybrid CMOS-MTJ circuits. Their non-volatile nature makes them ideal candidates for register replacements; they could be used in low power applications since they have no leakage power. They can also be used to create small 2D-memory arrays such as those used for look-up tables (LUT) on FPGAs. Furthermore, they can be used to create programmable logic arrays (PLAs) similar to the way floating gate transistors are used in NAND flash [3].

2.3 Mixed Signal and RF

MTJs can be utilized as spin torque nano-oscillators (STNOs). With their high-q characteristics as well as the ease of tunability, STNOs have seen ever-increasing interest in the RF and microwave community. Another appeal of STNOs is their size. With diameters on the scale of several nanometers, the idea of implementing oscillators capable of being easily integrated on chip has risen to the forefront of STNO research.

2.4 Microwave Signal Sources

The simplest of these applications are microwave signal sources. An STNO offers many advantages over traditional VCOs and crystal oscillators with regards to integrated circuitry. STNOs are very compact. The diameter of one STNO can be on the magnitude of tens of nanometers. This makes STNOs much smaller and thus more easily integrated on-chip than traditional means of tunable oscillators. Another advantage the STNO offers is its ultra-wideband frequency tunability. STNOs can be tuned across much wider ranges of frequency than traditional LC VCOs. This would result in needing fewer instances of oscillators on-chip to implement broadband functionality. Not only is there range of tunability an advantage, but also the ease of tunability. To tune the frequency of oscillation of an STNO, the dc bias current is adjusted. No complex tuning circuitry is needed other than adjustable current mirrors.

One of the biggest drawbacks and concerns for the longest time was the output power of the STNO. Our simulations show that the STNO outputs an AC current with amplitudes of a few micro amps. However, my current research involves designing a transimpedance amplifier capable of taking an input AC current with amplitudes of tens of nano amps, and outputting an AC voltage of millivolts, a signal much more suited for use with digital circuits or RF LO's. This transimpedance application also requires very high bandwidth and functions across a wide frequency range. Therefore, with the STNOs output of several micro amps and high tunability, it should be feasible to create an STNO capable of acting as a tunable signal sources when coupled with the appropriate transimpedance amplifier.

2.5 Phase-Locked Loops

Phase-locked loops (PLLs) are used in communication systems to tune to the appropriate frequency for receiving signals. PLLs essentially consist of a frequency tunable oscillator and a phase detector.

These PLLs are used commonly in receiving and demodulating RF signals. Depending on how accurate (jitter-free) the oscillator is, the PLL can increase its resolution pick up even smaller signals. STNOs may be able to fill the role as the oscillator and be part of many wide-band communication systems due to their frequency range. However, the phase noise of the oscillator must be small. Research suggests that STNO linewidths and phase noise are not great. However, this could be compensated for by the lack of tuning circuitry typically seen with LC-based oscillators, which adds phase noise as well.

2.6 Phased Arrays

As opposed to the mechanically scanning antennas seen in past years, the RADAR community has shifted towards the idea and implementation of electrically steered antenna. This is made possible by phased arrays, where the basic idea is to drive multiple antennas with various delays to steer the focus of the receiver or transmitter. This idea is portrayed in the image to the right. The phase delay on the antennas (the colored blocks) increases from left to right, making the direction of the antenna match the wave front, maximizing receive (or transmit) power. Due to the ease of tuning STNOs, as well as the lack of tuning circuitry needed otherwise, the STNO would be a good candidate for driving the antennas. Lincoln Labs, from MIT, are currently researching a phased array that utilizes an oscillator of 1.3GHz to steer their antenna. This frequency falls within the range of the STNO, and should be a feasible endeavor. Again, a drawback that may need to be addressed is the same one described in the application of STNOs in PLLs, the inherent phase noise may be worse than an LC tank with tuning circuitry.

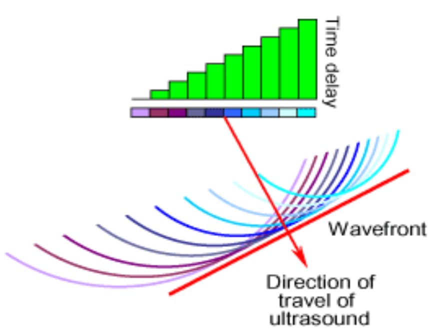

Figure 3: A phased array. Obtained from [#].

2.7 RF Filters

One problem with RF filters today is the tunability. An RF filter constructed of lumped elements cannot be tuned. The values of the capacitors and inductors are fixed. Filters constructed of microstrip lines, again, are fixed in dimension. There have been applications where the microstrip stubs can be adjusted with moving fixtures, allowing some tunability, but these are difficult to implement and need complex sensors and mechanical parts. The STNO can be used to construct RF filters. More importantly however, it can be used to construct a tunable filter. Mehdi Kabir and Professor Mircea Stan, at the University of Virginia, have simulated several types of RF tunable filters using STNOs. The narrow-notch filter shows a -12dB isolation across a small bandwidth of approximately 100MHz. While the filter response is not the best with regards to the isolation, it can be strengthened by utilizing another of their designs, which increases isolation to approximately -20dB. However, this results in a smaller bandwidth of isolation. The most appealing aspect of the STNO-based RF filters, is the capability of tuning the filter response frequency with just a voltage.

3. METHODS

The MTJ model used is based off of the Landau-Lifshitz-Gilbert equation and was developed by Mehdi Kabir and Prof. Stan. The model is coded in Verilog-A and we utilized Synopsis HSPICE to design, implement, and simulate various circuits involving the MTJ and STNO. First, we attempted to implement a proof-of-concept for the STT-RAM using this model. We were successfully able to change the states of the MTJ. Then, the microwave signal source was simply an MTJ with various DC voltages (and thus, currents) across it. We measured the resulting oscillatory behavior. We then attempted to implement an RF filter with the STNO. Ultimately, we were unable to reproduce the results seen by Kabir and Stan.

4. SIMULATION RESULTS

4.1 STT-RAM

We constructed a basic STT-RAM cell like the one shown in figure 2. We simulated a parallel to antiparallel transition to verify that the model was

working correctly. This simulation features a read, a write, and then another read. The yellow curve represents the current through a parallel state MTJ, the green curve represents the current through a antiparallel MTJ, and the blue curve represents the current through the MTJ that switches from parallel to antiparallel. The red curve is an input voltage pulse.

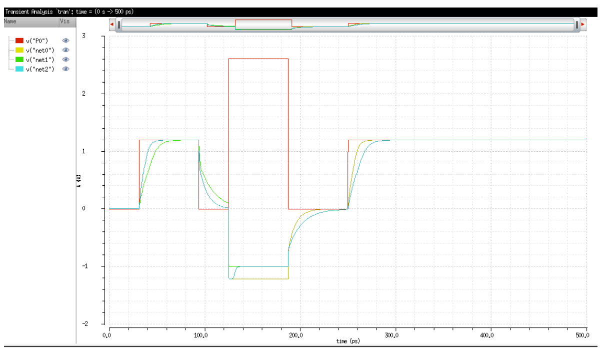

Figure 4: A MTJ transitioning from the parallel to antiparallel state.

4.2 Microwave Signal Source

The following data was obtained when various DC voltages were applied across the MTJ. From the plot, we can see that there is indeed a direct relationship between oscillation frequency and applied voltage. However, it was also observed that at lower oscillation frequencies, the oscillation became distorted, appearing more saw-tooth rather than sinusoidal. While this is not necessarily a problem when purely frequency is concerned, it could become an issue in applications where the shapes of the pulses are significant.

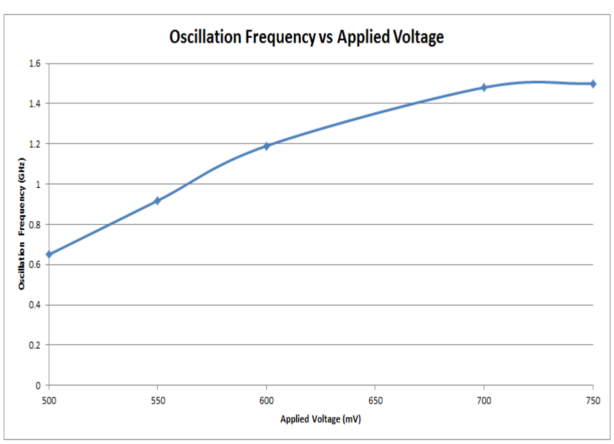

Figure 5: STNO oscillation frequency (GHz) VS applied voltage (mV).

5. CONCLUSION

Although we were unable to reproduce the RF filter results seen by Kabir and Stan, we were able to complete some basic proof of concept simulations with the MTJ and STNO models. That, combined with our research into on-chip RF applications, leaves us hopeful towards our future work with MTJs and STNOs.

The next step in our proof-of-concept is to combine the microwave signal sources we have tested with the transimpedance amplifier that Robert is currently designing. This will allow us to examine just how high of a voltage the STNO will be able to output after amplification. We will also do more experiments into phase noise and determine if the STNO phase noise is better than LC-based oscillators with tuning circuitry. This will lay the foundation for STNO-based PLLs and phased arrays.

ACKNOWLEDGEMENTS

We would like to thank Professor Stan and Mehdi Kabir for all their help with this project.

6. REFERENCES

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